CASSINI TRAJECTORY DESIGN DESCRIPTION

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The Cassini mission to Saturn will start a second phase in the exploration of the Saturnian system. The Cassini baseline mission is scheduled to be launched in October 1997 by the Titan IV/Centaur with Upgraded Solid Rocket Motor (SRMU) launch vehicle. Cassini uses four planetary gravity-assist flybys to gain the energy necessary to reach Saturn in June **2004.** This arrival date to Saturn provides a unique opportunity for a flyby of Saturn's outer satellite Phoebe on the final approach. Upon arrival at Saturn, a Probe will be delivered into the atmosphere of Titan and the Orbiter will continue its four year satellite tour which will be shaped by the repeated gravity assist flybys of Titan. This paper provides an overview of the interplanetary trajectory design, the Titan atmospheric Probe delivery, and the satellite tour.

INTRODUCTION

NASA's Cassini mission will send the first spacecraft- S/C to visit. the Saturnian system in more than two decades, since the unprecedented flybys of the Voyager S/C in 1980 and 1981. Unlike Voyager, the Cassini S/C will carry a Probe, provided by the European Space Agency, that will be released into the Titan atmosphere relaying science data to the Orbiter. The Orbiter will store the Probe data and transmit it. back to Earth at a later time. Another major difference from Voyager, is the duration of the science encounter. Cassini will investigate Sat-urn, its rings, satellites, and magnetosphere for four years.

The Cassini baseline or primary mission is scheduled for launch in October 1997 using the Titan IV-SRMU/Centaur. Because the launch vehicle cannot provide enough energy to fly a direct trajectory to Saturn, Cassini will fly a Venus-Venus-Earth-Jupiter Gravity Assist. (VVEJGA) trajectory, shown in Figures 1 and 2, to increase the energy of the trajectory with each planetary flyby. A deterministic or Deep Space Maneuver (DSM), whi ch is required throughout the launch period, will be executed after

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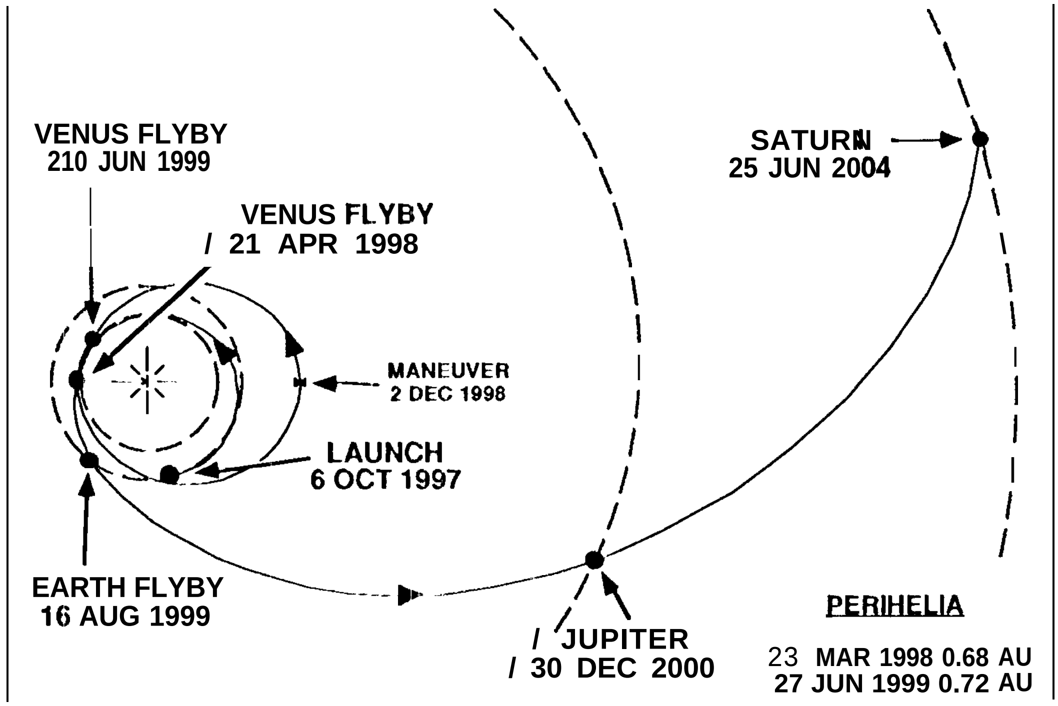

Figure 1. Cassini-VVEJGA October 1997, Interplanetary trajectory.
Launch Date: October **6, 1997** ; Arrival Date: June 25, 2004

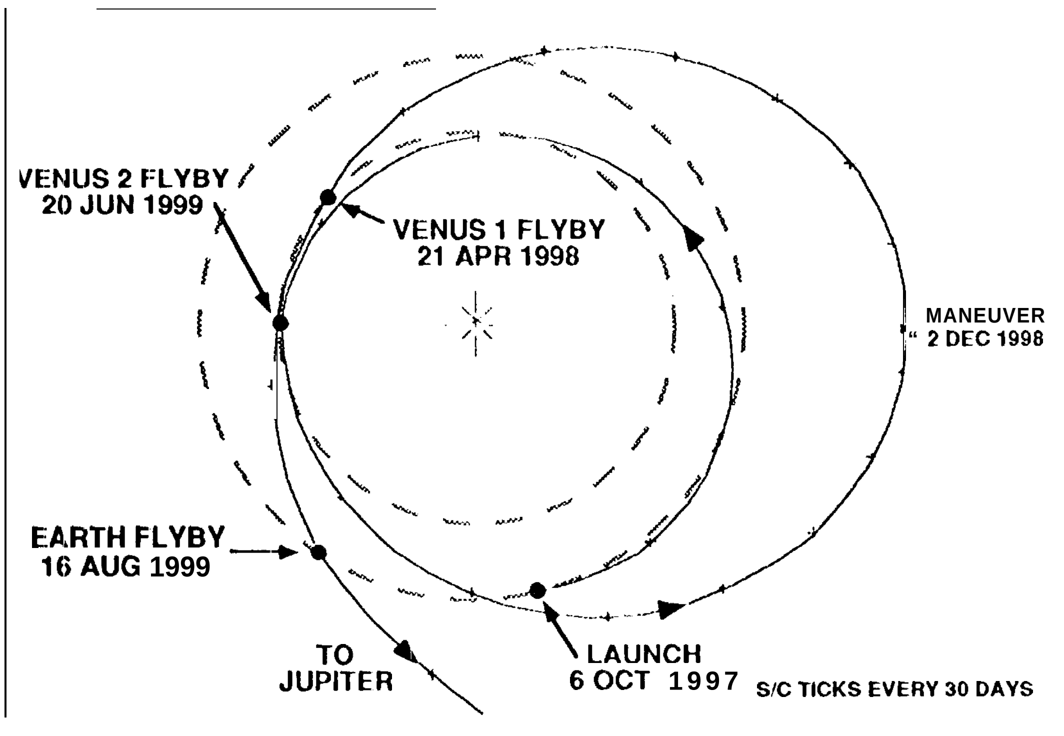

Figure 2. Cassini-VVEJGA October 1997, Inner Solar System trajectory.
Launch Date: October 6, 1997 ; Arrival Date: June 25, 2004.

Venus 1 (April 1998) to lower perihelion and place the S/C on the proper course to encounter Venus for a second time in June 1999. The S/C will be Sun pointed, except for maneuver execution, when within one Astronomical Unit (AU) of the Sun allowing the High Gain Antenna (HGA) to shade the rest of the S/C. During this time, communication with Earth will be achieved using the Low Gain Antenna (LGAs). After the Earth flyby in August 1999, the Cassini S/C will. be on its way to the outer planets. The Jupiter flyby occurs in December 2000. The science obtained during the interplanetary cruise phase is limited primarily to gravitational wave searches during three successive Sun oppositions beginning December 2001.

Saturn Orbit Insertion (SOI) occurs June **25, 2004, 6.7** years after launch. This arrival date enables a distant flyby of the outer satellite Phoebe 19 days before SOI. The initial orbit is designed to target the combined Orbiter/Probe S/C to Titan with the proper approach speed and accuracy. On November 6, 2004, approximately four months after SOI, the Huygens Titan Probe will be separated from the Orbiter. Two days after separation, the Orbiter performs the Orbit Determination Maneuver (ODM) to ensure that the Orbiter will not follow the Probe into Titan's atmosphere and to establish the proper geometry for Probe data relay. Probe entry occurs at the first Titan encounter on November 27, **2004**.

The orbital tour lasts 4 years which provides opportunities for ring imaging, magnetospheric coverage, and radio (Earth), solar, and stellar occultations of Saturn, Titan, and the ring system. A total of 33 close Titan flybys occur during the baseline tour; these are to be used for gravity assist control of the Saturn orbits as well as for Titan science acquisition. The S/C is also targeted for 4 close flybys of selected icy satellites and makes a total of 29 more distant satellite encounters. At this early stage, there are many factors which may eventually cause the tour profile to diverge from that presented here.

The baseline tour concludes in June, 2008, for a total mission duration of 10.7 years. Nothing in the design of the tour precludes an extended mission.

LAUNCH VEHICLE DESCRIPTION

A Titan IV-SRMU/Centaur launch vehicle will inject the Cassini S/C into the interplanetary trajectory to Saturn. Launch will originate from Cape Canaveral Air Force Station, launch complex **40** or 41. The Titan IV vehicle is a United States Air Force (USAF') launch system consisting of a two stage Titan IV core vehicle, two Type 11 solid rocket motors, a Centaur upper stage and a 66 ft. long payload fairing. The integration of the S/C and the launch vehicle is the responsibility of the NASA Lewis Research Center (LeRC) Launch Vehicle Project Office, LeRC provides the official performance quotation to the Jet Propulsion Laboratory (JPL) . Martin Marietta Corporation (MMC) is the USAF prime contractor for the launch vehicle system. MMC evaluates the payload capability and maximizes launch vehicle performance given the target conditions (Launch Energy per unit mass (C3), Declination of the Launch Asymptote, and the Right Ascension of the Launch Asymptote).

BASELINE INTERPLANETARY TRAJECTORY

Launch Period

The current nominal launch period of the baseline Cassini trajectory opens on October 6, 1997, and closes on October 30, 1997 providing a 25-day launch period. A contingency launch period might be included depending on trajectory performance and other project considerations. The opening of the nominal launch period is chosen to be the earliest launch date for which mission performance requirements are met and the Earth flyby altitude is not lower than 500 km. Lower altitudes than this will result in undesirable penalties in satisfying Earth swingby requirements. The close of the nominal launch period is constrained by the increase in magnitude of a required maneuver in the launch-to-Venus leg of the trajectory. Launch dates which minimize the interplanetary cruise duration are a function of the Saturn arrival date. The Saturn arrival date is constrained by launch vehicle performance, trajectory characteristics, and mission requirements placed on both the Orbiter and the Probe. An analysis of the launch/arrival space was carried out at JPL to identify the optimal trajectory for each launch date within the launch period. A more complete description of this study can be obtained from Reference 1.'

Trajectory Events

The Centaur/Cassini stack will be injected initially to the inner solar system after the Centaur upper stage completes its second burn which lasts approximately eight minutes. Shortly after injection, a Collision and Contamination Avoidance Maneuver is executed to separate the upper stage from the S/C such that the upper stage will not impact Venus or the S/C. The first Trajectory Correction Maneuver (TCM) is performed three t_o four weeks after launch to correct for injection dispersions.

Table 1 provides a summary of events that apply only to the reference trajectory which is the trajectory for the opening of the nominal launch period of the baseline trajectory. Other trajectories within the launch period are characterized by minor differences in quantities such as flyby dates and altitudes, maneuver dates anti magnitudes, etc. During the last five days of the launch period, a deterministic maneuver appears in the launch-to-Venus leg of the trajectory. This maneuver increases in magnitude at a rate of about 23 m/s per day, and it reaches a value of about 100 m/s by Oct. 30, 1997. This maneuver results when the second Venus flyby reaches its minimum allowed flyby altitude of **300** km which in turn establishes an upper limit to the Earth flyby dates and altitudes. As a consequence of all this, the Jupiter flyby altitude and date also reach a limit for the last five days of the launch period.

The perihelion of the initial orbit, is 0.68 AU and is the closest the S/C flies to the Sun. 'l'his perihelion occurs on March 23, 1998. The first Venus encounter occurs on April 21,1998, 198 days after launch. 'l'he Venus flyby trajectory is shown in Figure 3. The S/C approaches Venus from the Sun direction. Venus occults the S/C from the Sun for about 16 minutes and from the Earth for

Table 1. MISSION EVENTS

Mission Events	Start Date	Days from Launch	Comments
Launch	6-Ott-97	**0**	C3 = 18.1 km^2/s^2
Aphelion	1-Nov-97	26	Sun range = 1.02 AU
DSM	16-Mar-98	162	Av = O m/s; ΔV>0 for launch dates after 10/25/97
Perihelion	23-Mar-98	169	Sun range = 0.68 AU
Venus 1 flyby	**21-Apr-98**	198	Altitude = 300 km; Velocity = 11.8 km/s
HGA	27-Nov-98	417	On when Sun-s/c-Earth angle < 30° at 1.5 AU
DSM	2-Dec-98	423	AV = 466 m/s
Aphelion	4-Dee-98	424	Sun range = 1.58 AU
LGA	3-Feb-99	485	Thermal constraints restrict HGA usage
Venus 2 Flyby	**20-Jun-99**	622	Altitude = 2207 km; Velocity =- 13.0 km/s
Perihelion	27-Jun-99	629	Sun range = 0.72 AU
Earth Flyby	**16-Aug-99**	680	Altitude = 517; Velocity = 19.1 km/s
HGA	2-Sep-99	696	On permanently
•Conjunction	13-May-00	**950**	
•Opposition	28-Nov-00	**1149**	Gravity Wave Opportunity
Jupiter flyby	**30-Dec-00**	1181	Altitude = 141 R_J; Velocity = 11.5 km/s
•Conjunction	7-Jun-01	**1340**	
•Opposition	16-Dec-01	**1532**	Gravity Wave Experiment - opportunity ± 20 days
•Conjunction	21-Jun-02	**1719**	
•Opposition	27-Dec-02	**1908**	Gravity Wave Experiment - opportunity ± 20 days
•Conjunction	1-Jul-03	2094	
Science on	25-Dec-03	2271	Science turn-on 6 months before arrival
•Opposition	4-Jan-04	**2281**	Gravity Wave Experiment - opportunity i 20 days
SOI	**25-Jun-04**	**2454**	AV =625 m/s
•Conjunct-ion	8-Jul-04	**2467**	
PRM	10-Sep-04	**2531**	AV = 326 m/s
Probe Separation	6-Nov-04	**2588**	
ODM	8-Nov-04	2590	Av = 57 m/s
Probe Entry	27-Nov-04	**2609**	
Titan 1 flyby	**27-Nov-04**	**2609**	Altitude = 1500 km; Velocity = 5.9 km/s
EOM	**25-Jun-08**	3915	End of 4-year tour

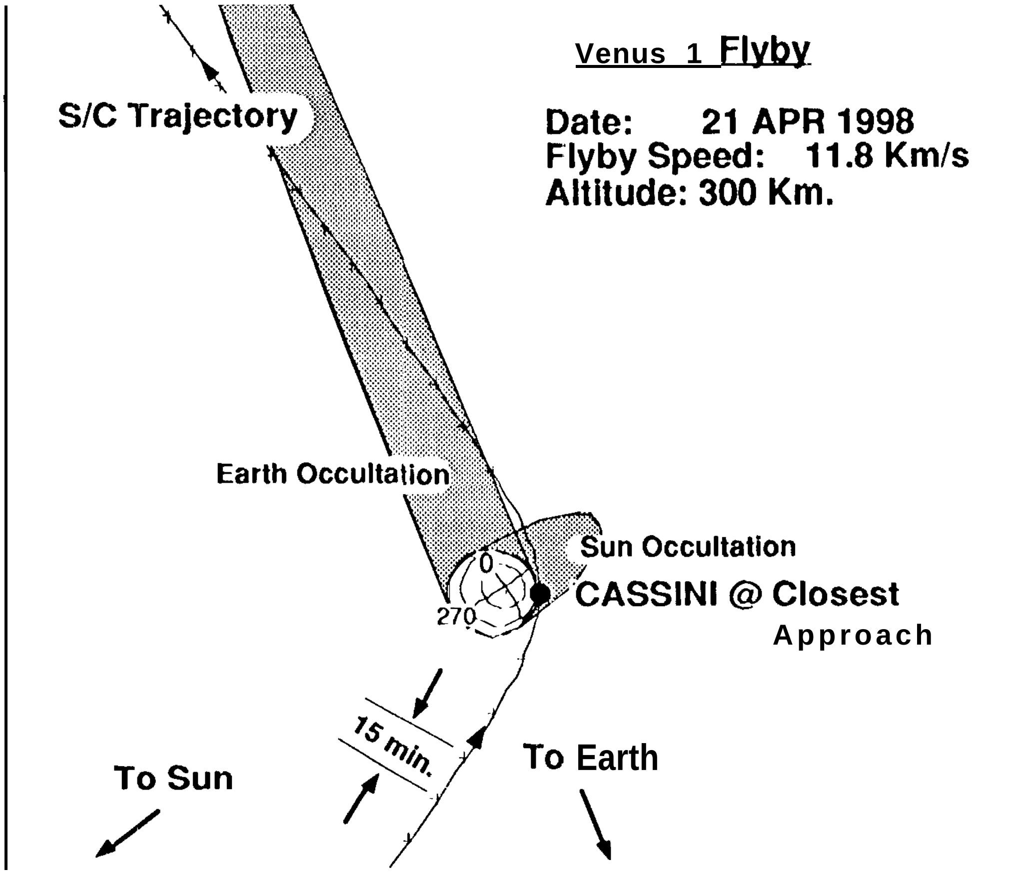

Figure 3. Venus 1 Flyby, Trajectory North Pole View.

about 2 hours. The Earth occultation zone starts 15 minutes after the S/C leaves the Sun occultation zone, Closest approach occurs in the Sun occultation zone which will last about 16 minutes. At closest approach, the altitude is 300 km, the minimum permitted, and the velocity relative to Venus is 11,8 km/s. Venus targeting accuracy is improved using two TCMs, 60 and 20 days before closest approach, and a clean--up maneuver 20 days after the flyby.

A few days before aphelion of the second heliocentric orbit, a deterministic maneuver will be performed to reduce perihelion and target the trajectory for the second Venus flyby. The magnitude of this maneuver ranges from 350 m/s to 470 m/s depending on the launch energy and the launch date, 'l'his maneuver magnitude decreases for later launch elates within the launch period.

The second Venus flyby occurs on June 20,1999, 424 days after the first Venus encounter. The Venus-2 flyby trajectory is shown in Figure 4 . Venus is approached from the anti-Sun direction. Closest approach occurs after the S/C exits a 15 minute Earth occultation zone. At closest. approach, the altitude is 2207 km, and the Venus-relative velocity is 13 km/s. Venus 2 targeting maneuvers take place 60 and 20 days before closest approach and

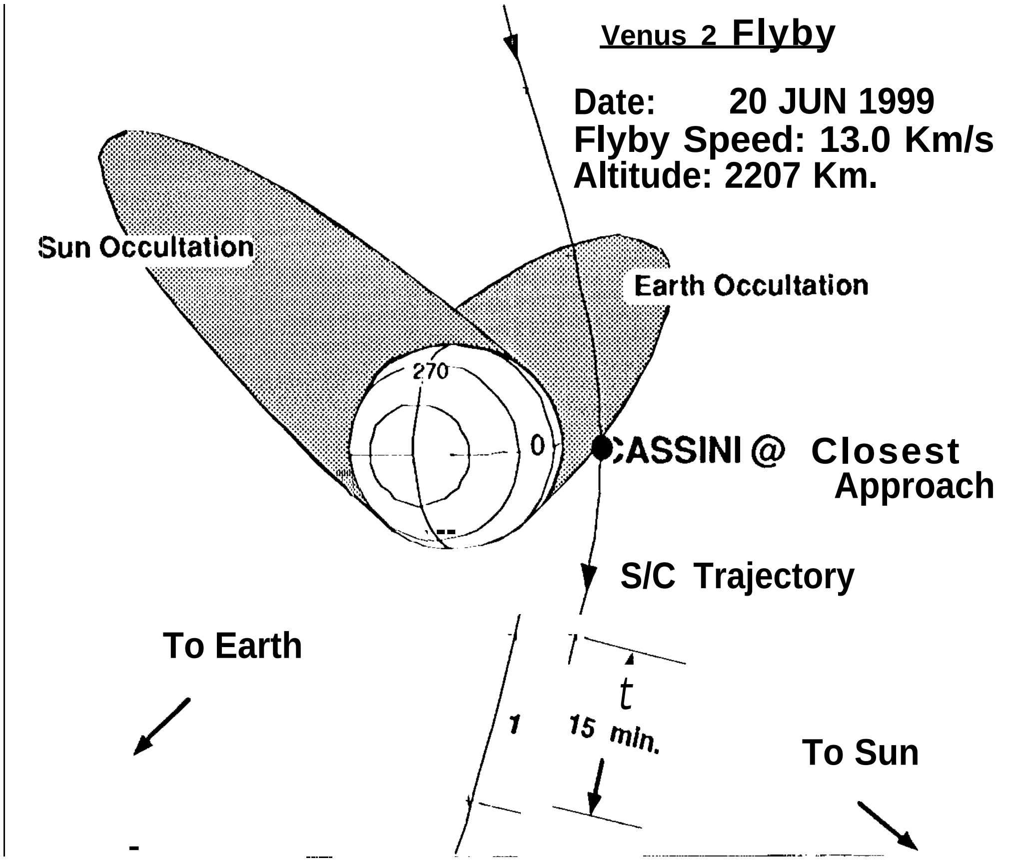

Figure 4. Venus 2 Flyby, Trajectory South Pole View.

10 days after the flyby. Perihelion of the second heliocentric orbit occurs a week after the second Venus flyby on June 27, 1999, at, a distance from the Sun of 0.72 AU.

The geometry of the VVEJGA trajectory is unique since it provides the opportunity of a double planetary flyby, Venus 2 to Earth, within 56 days. The Earth flyby trajectory is shown in Figure 5. The Earth is approached from the Sun direction. Closest approach occurs on August 16, 1999, shortly before a 30 minute Sun occultation. The altitude at closest approach is 517 km, and the Earth-relative velocity is 19.1 km/s. Targeting maneuvers will take place 30 and 10 days before closest. approach and a TCM clean-up maneuver 20 days after the flyby.

The Jupiter flyby occurs on December 30, 2000, at an altitude of 141 Jupiter radii (10.1 million km), and a Jupiter-relative velocity of 11.6 km/s. The flyby altitude is dictated by gravit.y-assist considerations. Lower Jupiter flyby altitudes would result in substantial AV penalties. Targeting maneuvers are executed 80 and 20 days prior to the flyby and a TCM clean-up maneuver 20 days after the flyby,

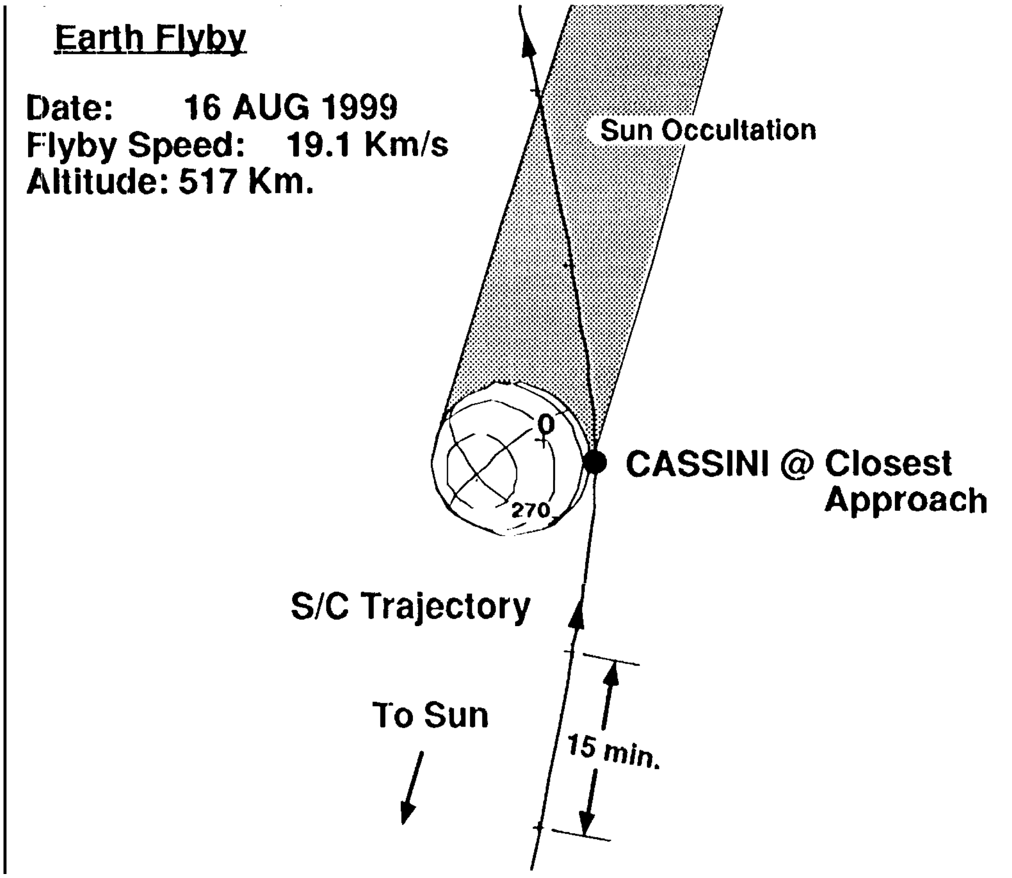

Figure 5. Earth Flyby, Trajectory North Pole View.

VVEJGA TRAJECTORY DESIGN TOOLS AND ANALYSIS

The VVEJGA trajectory design is accomplished using two trajectory optimizer programs developed at JPL. MIDAS, Reference 2, was used to perform very preliminary studies to determine fundamental trajectory characteristics such as the sequence of flyby bodies, MIDAS models S/C trajectories using patched conies. The output information provided by MIDAS is then used as initial conditions to the PLAnetary Trajectory Optimization (PLATO) program, Reference 3. PLATO uses multi-conic propagation methods to more accurately model the trajectory dynamics and employs a more sophisticated optimization scheme. However, PLATO requires a good guess of initial conditions in order for convergence to occur. A complete study (Ref. 1) of all possible trajectories launching in the September-October-November 1997 range and arriving at Saturn from April 2004 to December 2005 was carried out as part of the launch/arrival trajectory analysis process using PLATO.

In PLATO, optimizing a trajectory means minimizing a cost function which in this case is the total deterministic post-launch AV required. Variables to consider are the launch V-infinity, the times of the deterministic maneuvers, and the planetary flyby parameters such as: the altitude, B-plane(hyperbolic orientation) angle, and the times of each planetary gravity-assist flyby. These independent variables are allowed to change, subject to upper and lower limits that may be placed on any or all of the variables. These parameters may be subject to constraints arising from mission operations, such as the time or direction of a maneuver. Other constraints come from science considerations or are physical in nature. For example, a lower limit on flyby altitude is specified so as to prevent the S/C from impacting the flyby planet. or entering its atmosphere.

The solution for an optimized Cassini VVEJGA trajectory usually contains one or more deterministic maneuvers which are non-zero AVIS. Other maneuvers are statistical and are nominally zero, but in actual flight. become non-zero due to maneuver execution errors, orbit determination errors, and planetary ephemeris uncertainties. For example, the first TCM (TCM-1), performed about three to four weeks after launch, is a statistical maneuver to correct for the injection errors of the Centaur upper stage.

The analysis and design of the Cassini-VVEJGA trajectory is a complex, time-consuming process since the optimization of four planetary flybys is required. The resulting set of trajectories meet the injection capability of the launch vehicle.

VVEJGA MISSION PERFORMANCE

Mission performance is measured in terms of End of Mission (EOM) AV, defined as the amount of AV available with the bipropellant remaining in the tanks after completion of the four year satellite tour.

Figure 6 provides a plot of launch date vs launch vehicle injection margin in the left axis and EOM AV in the right axis for the baseline trajectory. Both curves are constructed by combining local and global optimum trajectories; see Reference 1 . This combination of trajectories optimizes performance throughout the launch period. Local optimum trajectories are utilized from the beginning of the launch period until October 13 (transition point) and global optimum trajectories are used from that date until the close of the launch period, 'l'he C_3 decreases for the local optimum type of trajectories as the launch date is delayed while the global optimum trajectories use a fixed C_3 of 20 km^2/s^2 in this easel. Injection margin increases with the decrease in C3 for the local optimum trajectories but of course remains constant for the global optimum trajectories since the C_3 is constant. EOM AV remains almost flat, -130 m/s, from the opening of the launch period to the transition point, where the FOM AV starts increasing to a value of about 215 m/s on October 25, 1997. From this launch date on, the EOM AV decreases sharply due to the rapid increase in the magnitude of the launch to Venus 1 maneuver.

1 The selection of the fins] fixed C_3 will be driven primarily by launch vehicle considerations

Cassini's 3132 kg of total propellant is used for deterministic and statistical (navigation) maneuvers, attitude control, propellant line clearing maneuvers, and science turns. Navigation maneuvers include interplanetary TCMs, an ODM occurring about, four months after orbit. insertion, and TCMS for satellite-tour navigation once the S/C is in orbit about Jupiter.

Table 2 shows the mass summary for the baseline mission for the opening of the launch period. Table 3 shows a summary propellant consumption profile throughout the mission for a launch date on Oct. 6, 1997, and a C_3 of 18.1 km^2/s^2. A sample EOM AV is also illustrated in Table 3. "

Table 2. **CASSINI** MISSION MASS **SUMMARY**[1].

	Mass (kg)
Dry S/C (Orbiter) Allocation	**2150**
Probe Interface Hardware Allocation	**30**
Probe Allocation	**343**
Bipropellant (constant load through launch period)	**3000**
Holdup and Residuals =- 81 kg	
Required for AV = 2834 kg (I_{sp} = 308s)	
Margin = 85 kg	
Hydrazine	132
Attitude & Articulation Control Subsystem (AACS) = 46 kg	
Required for AV = 52 kg (Is_p = 215s)	
Margin = 34 kg	
Total 'Wet S/C (including Probe)	**5655**
Launch Vehicle Adapter Allocation	**190**
'I'oLa] Injected Mass	5845
Titan IV (SRMU)/Centaur Capability (C_3=18.1 km^2/s^2)	**6323**
injection Margin	**478**

SATURN ARRIVAL/INITIAL ORBIT

The Cassini S/C encounters Saturn's outer moon Phoebe about 19 days before Saturn arrival at a flyby distance of -840,000 km. This is the only opportunity for a Phoebe flyby during the mission and constrains the Saturn arrival date to be in late June 2004. A single main engine burn of about 90 minutes duration places the S/C into orbit about Saturn on June 25, 2004. SOI occurs at a distance of 1 .3 Saturn radii and brings the S/C closer to Saturn and the inner rings than will occur during the rest of the satellite tour, representing a unique science opportunity. 'l'he post-SOI orbital period is 15? days and the inclination with respect to the Saturn equator is 17°. The initial orbit is designed to target the combined Orbiter/Probe S/C to Titan with the proper approach speed and accuracy. Therefore, although the initial orbit forms the beginning of the orbital tour, the design of

[1] For the openning of the launch period on Oct. 6, 1991.

[2] Based upon NASA LeRC performance quotation (June 3, 1993) .

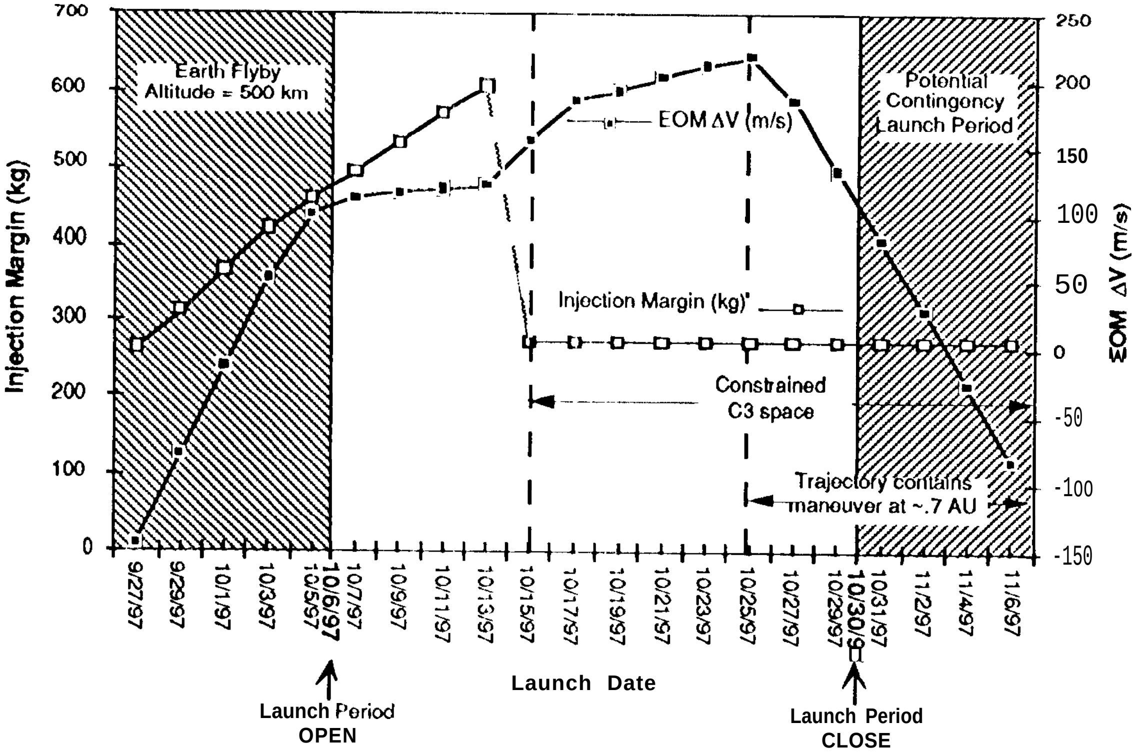

Figure 6. Saturn Arrival and Initial Orbit.

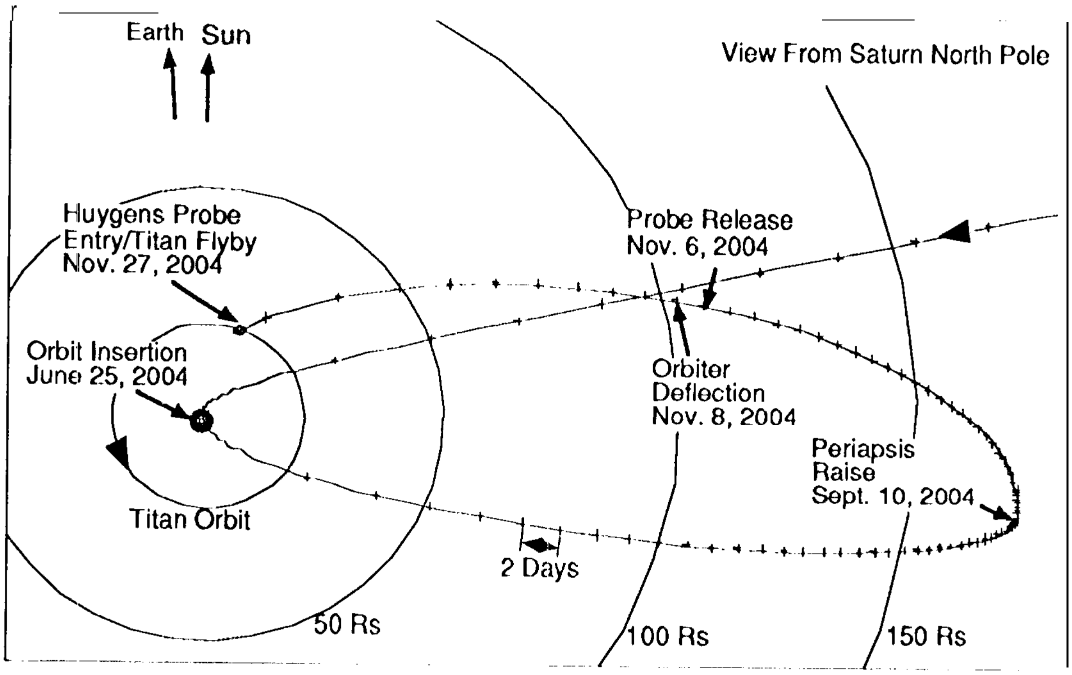

Figure 7. Saturn Arrival and Initial Orbit, .

Table 3. PROPELLANT CONSUMPTION PROFILE

	AV (m/s)	Specific Impulse (sec)	Initial Mass (kg)	Delta Mass[1] (kg)
Adapter drop			5845	**190**
DSM 1	0	308	5655	
DSM 2	466	308	5655	**808**
Interplanetary NAV TCM Bipropellant	191	308	4847	297
Pre-SOI AACS			4550	31
SOI	548	**308**	4519	749
SOI Delay + Gravity Loss	76	**308**	3770	93
PRM	326	**308**	3675	376
First Orbit TCM Bipropellant	38	**308**	3299	41
Probe Release			3258	343
ODM	57	308	2915	55
Deterministic Tour Bipropellant	200	308	2860	183
Tour NAV TCM Biprop.	271	**308**	2677	230
Tour NAV TCM Hydrazine	**43**	215	2447	50
Post-SOI AACS			2397	15
TOTALS	2217			3422

EOM Bipropellant/Hydrazine AV Margin (m/s) :	110/34
Total Usable Bipropellant required for nominal (kg)	2834
Total Usable Bipropellant left at EOM (kg)	85
Total Mission Bipropellant	**3000**
Total Usable Hydrazine required for nominal (kg)	96
Total Usable Hydrazine left at EOM (kg)	34
Total mission Hydrazine (kg)	132

[1] Numbers represent **propellant masses**, except where bold, in which case **the numbers reflect hardware masses.**

the initial orbit is driven mainly by Probe mission requirements rather than tour science objectives.

PROBE MISSION

On November 6, 2004, approximately four months after SOI, the Huygens Titan Probe will be properly oriented, spun, and released, At least two navigational maneuvers will be performed before separation to ensure accurate targeting for atmospheric entry. Two days after separation, the Orbiter performs the ODM to ensure that the Orbiter will not. follow the Probe into Titan's atmosphere and to establish the proper geometry for Probe data relay. 'I'he ODM delays the Orbiter's arrival at 'Titan by 4 hours with respect to Probe entry in order to establish the required relay link geometry. 'I'he overflight position for the Orbiter will be suitable for relay geometry and favorable for the tour design. The initial Titan flyby altitude of the Orbiter is 1500 km. If for some reason the Probe cannot be delivered at the initial Titan flyby, the Probe will be delivered at the second Titan encounter.

The Probe will be targeted for a high latitude landing site on the day side of Titan. In order tominimizetrajectory dispersion and thus enhance data relay link performance, and to avoid Probe skip-out, the Probe entry angle into the atmosphere will be relatively steep at -64°. The B-plane angle of the Probe aim point is currently baselined at -80°. No Earth or Sun occultations of the S/C by Titan occur during the initial flyby.

SATELLITE TOUR

This Section describes the baseline Saturn orbital tour. A generalized tour strategy has been developed and implemented which attempts to satisfy often conflicting science requirements given mission and S/C constraints. The resulting tour is referred to as the **92-01** satellite tour. At this early stage, however, there are many factors which may eventually cause the tour profile to diverge from that presented here.

The orbital tour begins at SOI and lasts four years. Figure **8** shows all tour orbits in a rotating coordinate system in which the Sun direction is fixed, Since the Figure has been projected onto the Saturn equatorial plane, the inclination of the orbits is not apparent. Each orbit is referred to as a petal due to the resemblance of Figure **8** to a flower. The 92-01 tour consists of 63 Saturn orbits in various orientations, with orbital periods ranging from 7 to 152 days, and Saturn periapses ranging from about 2.7 to 7.6 Saturn radii . Ascending and descending node crossings of the S/C orbit are restricted by the requirement to avoid hazardous regions in the ring system. Orbital inclinations with respect to the Saturn equator range from 0° to 76°, providing opportunities for ring imaging, magnetospheric coverage, and radio (Earth) , solar, and stellar occultations of Saturn, Titan, and the ring system.

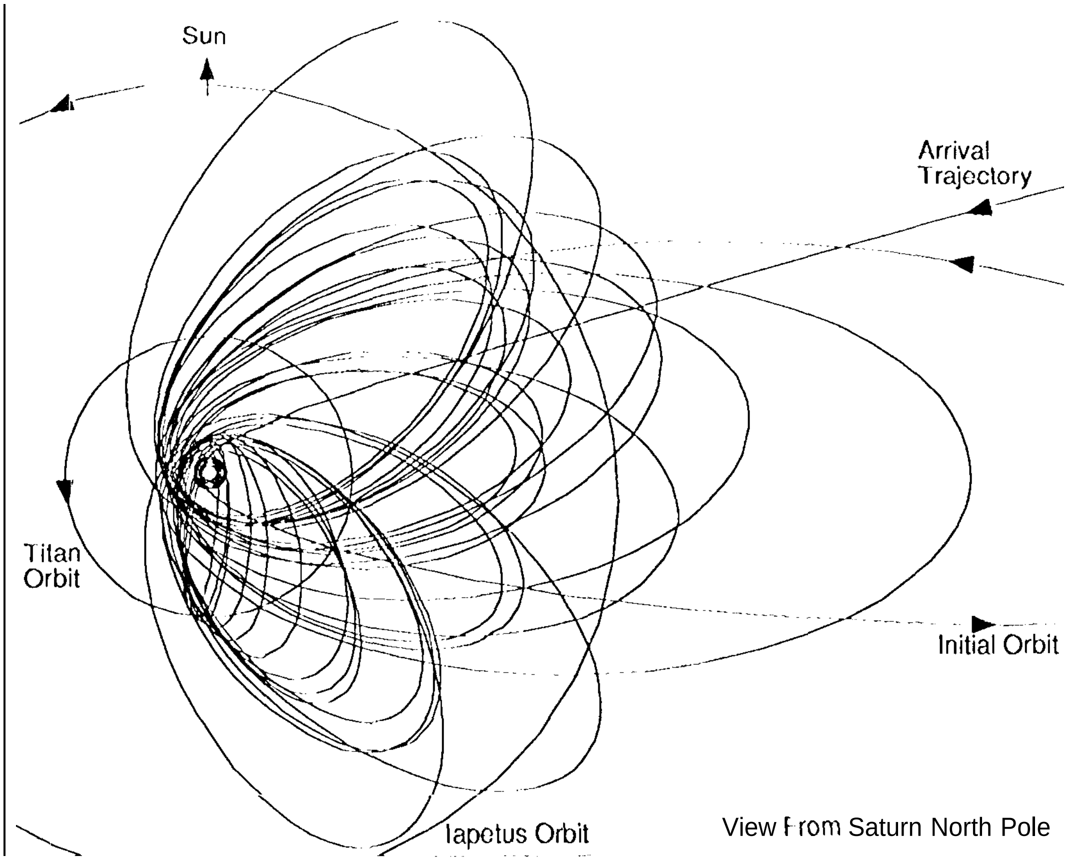

Figure 8. Saturn Orbital Tour

A total of 33 close Titan flybys occur during the baseline tour; these are to be used for gravity assist control of the Saturn orbits as well as for Titan science acquisition. Note that a Titan flyby does not occur on every rev about Saturn. The S/C is also targeted for 4 close (altitude <= 1000 km) flybys of selected icy satellites, and makes a total of 29 more distant (altitude <= 100,000 km) satellite encounters.

Since Titan is the only Saturnian satellite massive enough to provide any appreciable gravity assist, the tour orbits must always include a nearly free return to Titan. Although small propulsive maneuvers are included to allow some flexibility, the number and sizes of these. maneuvers must be minimized. Science requirements dictate that the orbit be rotated with respect to the Saturn--Sun line in order to obtain both low phase angle coverage of Saturn and sampling of the Saturn magnetotail region which lies in the anti-Sun direction. Investigation of the Saturn magnetotail region also requires near polar orbits. Inclination must also be nonzero for ring imaging, Saturn/ring occultations, high latitude atmosphere and magnetosphere science, complete Titan coverage, and some Iapetus flybys. Thus a wide range of orbit orientations and inclinations is required. A description of both the tour strategy employed and the resulting trajectory characteristics is presented below.

Since the initial orbit. apoapsis is over the dawn terminator of Saturn, the initial orbit petal is rotated counter-clockwise in order to obtain low phase angle coverage of Saturn. Orbit period is reduced to maximize both Saturn coverage and the number of satellite flyby opportunities. During the first 10 Titan flybys (Saturn revs 0 to 16) the orbit petal is rotated counter-clockwise as much as possible such that sufficient time exists to eventually rotate the orbit petal clockwise to achieve the magnetotail orientation near the end of the tour. A fundamental goal is to reach the magnetotail petal orientation (apoapsis along anti-Sun direction) by about 3 years into the tour, which leaves sufficient time to increase the inclination for the high inclination sequence by the end of the mission.

During the initial counter-clockwise petal rotation, close targeted flybys of satellites Rhea and Dione are obtained. inclination is also increased for a short time to achieve a close Iapetus flyby and a sequence of Saturn/ring diametric occultations. Titan flybys 11 to **24** (Saturn revs 17 to 35) rotate the orbit petal clockwise towards the anti-Sun direction. Along the way, a close Enceladus flyby is obtained as well as a second Saturn/ring diametric occultation sequence. Titan flybys 25-33 (Saturn revs 36 to 63) are used to incrementally raise the orbit inclination to the final value of 76°.

Titan flyby altitudes range from **950** to **16,200** km and flyby velocities range from 5.5 to 6.0 km/s. While many science instruments favor minimization of Titan flyby altitudes, navigation and S/C safety considerations tend to favor higher flyby altitudes. A Titan flyby altitude reduction strategy is employed to slowly lower the S/C altitude each flyby until the minimum permitted value of 950 km is reached. Ten Earth and 10 Sun Titan occultations occur ranging in duration from 5 to 21 minutes. Five Earth and 5 Sun occultations occur during the first two Saturn/ring occultation sequences and 27 Earth and 9 Sun occultations are obtained during the high inclination sequence near the end of the tour. 'l'he Saturn occultation durations range from 2.7 to 11 .0 hours. Stellar occultations undoubtedly exist but have not yet been identified.

Deterministic maneuvers are required between all Titan to Titan resonant orbits in order to change the aim point and are often required to achieve the required phasing for targeted icy satellite flybys. The deterministic AV required by the 92-01 tour is within the 200 m/s allocation. Statistical, or navigation, AV'S are also planned both before and after each Titan flyby (within a few days) and at orbit apoapsis. The total statistical AV allocation for the tour is 314 m/s.

The baseline tour concludes in June, 2008, with the S/C in an orbit. period of 7.1 days, inclination of 76°, and periapsis radius of 2.7 Saturn radii .

SECONDARY AND BACKUP TRAJECTORIES

To enable recovery from possible extreme launch delays, the Cassini project has selected a set of secondary and backup mission opportunities, summarized in Table 4. These missions make use of the Venus-Earth-Earth Gravity Assist (VEEGA) trajectory concept . Secondary missions are allowed to have a launch date less than six months after the baseline mission. 'l'his mission protects against launch slips that occur after hardware delivery, and can be diagnosed and fixed within a short time, but not quickly enough to meet the baseline launch schedule. Science return can be degraded slightly in light of the competing pressure to launch the S/C if a problem delaying the baseline mission is identified and solved. Backup missions are required to be launched at least six months after the baseline mission opportunity, and to have the same science return profile as the baseline. Backup missions are kept in the mission set to protect against launch slips from programmatic or technical issues that cause a long launch delay.

The current. trajectory set contains a secondary mission opportunity. This mission launches on a VEEGA December 199-/ type II[1] trajectory to Venus with a C_3 of 18.9 km^2/s^2, Figure 9. Venus closest approach occurs on June 4, 1998, at an altitude of -2350 km. After the Venus flyby, the S/C follows a type III trajectory transfer to Earth. Earth closest approach happens on Nov. 8, 1999 at an altitude of 2550 km. A deterministic manuever is executed to properly phase the S/C for the second Earth flyby which takes place on July 27, 2002, at an altitude of 500 km. Finally, The S/C arrives at Saturn on October 13, 2006. unfortunately, the cruise time for the secondary mission is two years longer than the baseline after a launch delay of about one month.

The backup mission opportunity launches on a VEEGA March 1999 type IV trajectory to Venus with a C_3 of 14.5 km^2/s^2, Figure 10. Venus closest approach occurs on June 11, 2000 at an altitude of --1407 km. Following the Venus flyby, the S/C goes on a type II trajectory transfer to Earth. Earth closest approach happens on August 27, 2001 at an altitude of 2800 km. This Earth flyby puts the S/C into a 3 year resonant loop to encounter the Earth for a second time. A deterministic manuever is executed to properly phase the S/C for the second Earth flyby which takes place on August 22, 2004 at an altitude of 500 km. The S/C arrives at Saturn on August 22, 2008.

The secondary and the backup trajectories have enough AV performance to carry out the mission with no degradation to the science return. That is, the mission contains a full 4-year tour with 33 Titan flybys. The significant difference between this missions and the baseline is a longer interplanetary cruise time, However, the longer cruise times cause a change in the power available due to the degradation of the Radioisotope Thermoelectric Generator power source. The available power level for the

[1] Type 1 trajectories have a heliocentric transfer angle between O and 180 deg., type II trajectories between 180 and 360 deg., and so on.

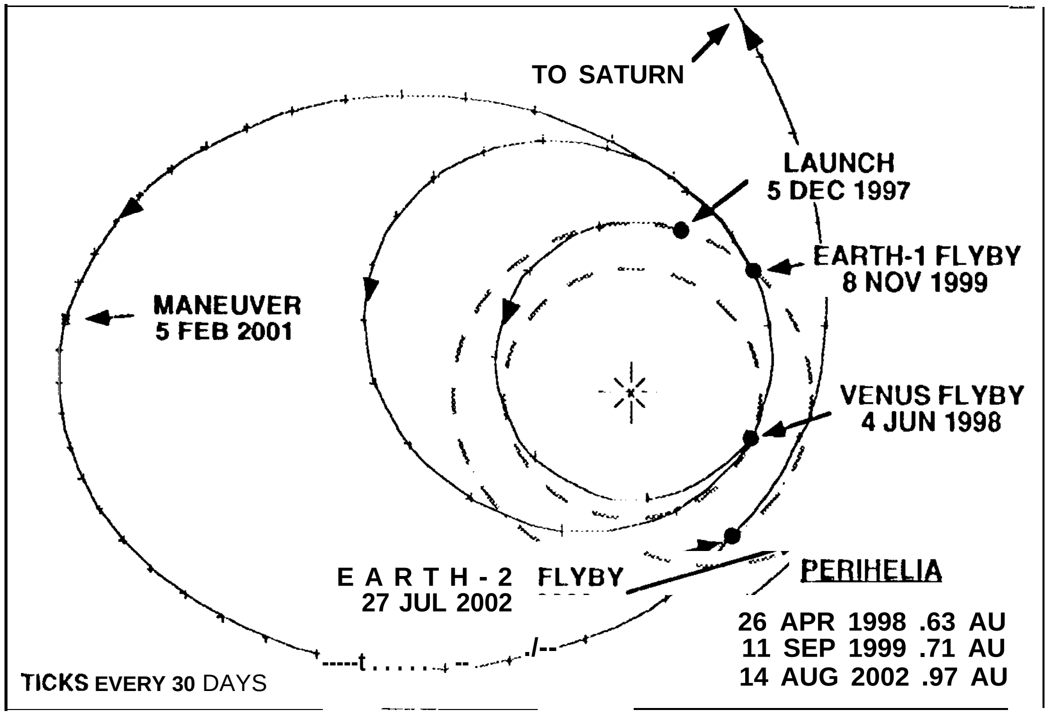

Figure 9. VEEGA97 - Inner Solar System Trajectory

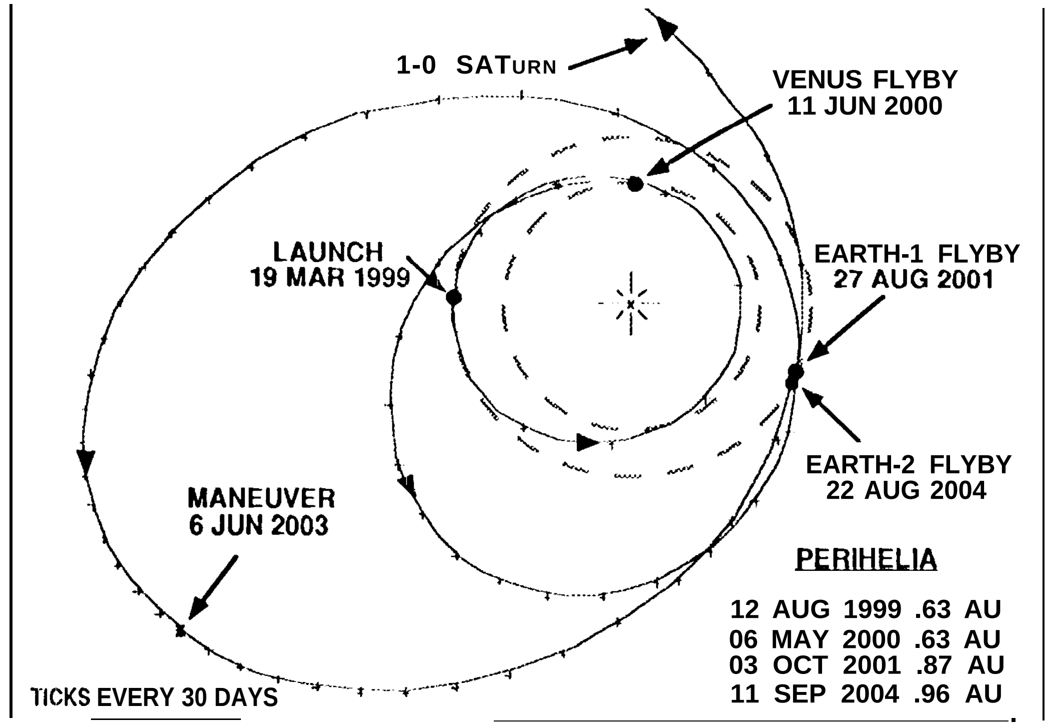

Figure 10. VEEGA99 - Inner Solar System Trajectory

backup mission at Saturn arrival is roughly equal to that available for the baseline mission at EOM (SOI + four years) . This would result in fewer instruments being allowed to operate at a given time, or less engineering support to a suite of instruments.

Table 4. SECONDARY AND BACKUP TRAJECTORIES.

Classification	Secondary	Backup
Trajectory Type	VEEGA	VEEGA
Launch Period	12/5/97 -12/22/97	3/19/99 - 4/5/99
Arrival Date	)0/13/2006	12/22/2008
Cruise Duration (years)	8.8	9.8
Satellite Tour (years)	4	4

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Nomenclature

AACS	Attitude and Articulation Control Subsystem.
AU	Astronomical Unit.
C3	Launch energy per unit. mass.
DSM	Deep Space Maneuver.
EOM	End of Mission.
HGA	High Gain Antenna,
LeRC	Lewis Research Center.
LGA	Low Gain Antenna.
JPL	Jet Propulsion Laboratory.
MMC	Martin Marietta Corporation.
NASA	National Astronautics and Space Administration.
ODM	Orbit Deflection Maneuver.
PLATO	PLAnetary Trajectory Optimization.
PRM	Periapsis Raise Maneuver.
SOI	Saturn Orbit Insertion.
SRMU	Solid Rocket Motor Upgraded.
s/c	Spacecraft,
TCM	Trajectory Correction Maneuver.
USAF	United States Air Force.
VEEGA	Venus-Earth-Earth Gravity Assist.
VVEJGA	Venus-Venus-Earth-Jupiter Gravity Assist..